Etchless Pedestal Chalcogenide Waveguides for Mid-IR On-Chip Sensing and Spectroscopy Applications

(Student paper)

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Etchless pedestal waveguides are demonstrated with confirmed long-wave IR transparency up to 12 µm. Direct etching of the chalcogenide layers is avoided by using Si micropatterning and thermal evaporation. Losses as low as 0.5 dB/cm were estimated, making the platform a promising candidate for on-chip sensing and spectroscopy.
Keywords: *Mid-IR, Waveguides, Chalcogenides, Spectroscopy, on-chip*

INTRODUCTION

The mid-infrared (mid-IR) spectral region (2.5-25 µm) is of great interest due to the unique molecular absorptions present predominantly between wavelengths of 2.5 and 15 µm. The close study of these absorptions can provide extremely useful information about a specimen of interest. Optical spectrometers are used to extract and study these absorptions, and these are typically bulky and expensive making them unattractive for widely-deployable on-site molecular analysis applications.

One of the most important performance considerations for integrated optical sensors and waveguide based on-chip spectrometers is low propagation loss across the desirable wavelength band of operation. The range of materials that can be used in the mid-IR and more specifically for long-wave IR applications, is quite limited. The reason behind this is usually the strong material absorptions emerging at longer wavelengths (oxygen related, phonon or free carrier absorption). Glasses are used in optics very extensively, with the most common glass family being the oxides. Oxides have good optical properties; however, they absorb light very strongly above ~4 µm. Chalcogenide glasses are not characterised by such absorptions and have shown to possess excellent properties such as wide infrared transparency (sometimes up to 20 µm), large refractive index (usually between 2 and 3) and high optical non-linearity [1,2].

Regardless of their huge potential, chalcogenide glasses have proven to be very delicate and as a result special care is required during their processing. More specifically, chalcogenides tend to be prone to chemically induced damage. Such chemicals include alkaline solutions used in photolithographic developers as well as ionised gases used in dry etching [3]. Nonetheless, several examples of chalcogenide waveguide platforms have been reported in the literature [3-6]. In these works, various methods of fabrication have been presented such as hot embossing [3], photolithography and etching [4], photodarkening [5] and micro-transfer moulding [6]. Even though low propagation losses of less than 0.5 dB/cm are estimated in [3] and [4], there are serious drawbacks associated with the high temperatures used in hot embossing as well as with the complex process tailoring required for waveguide layer etching of these materials. Therefore, there remains a great deal of potential for the development of new fabrication approaches for integrated chalcogenide waveguides.

As mentioned above, low waveguide propagation losses are considered a necessity when it comes to design an efficient on-chip spectrometer. In integrated waveguides, reducing sidewall roughness plays a major role in reducing the propagation losses. Rib waveguides are usually utilised when limited interaction between the propagating mode and the sidewall is necessary. However, this geometry is not suitable for applications where interaction between the mode and the outer medium is essential (i.e sensing). In such applications a ridge geometry is required. Furthermore, in devices relying on the use of very tight bends such as spiral waveguide spectrometers, the use of ridge waveguides is essential for keeping the radiation losses low while maintaining as small device footprint as possible.

In order to reduce the propagation loss induced by sidewall roughness, the post deposition processing of the chalcogenide layers must be completely eliminated. Instead of using lift-off which still requires a lift-off resist pattern removal step, we utilised a similar etchless process to that described in [7]. In this process, pedestals are formed on a Si wafer using standard photolithography and etching methods. The optical layers are then deposited on these pedestals. In that way, waveguides are formed without the need for etching the optical layers.

In this study, we fabricate and test a chalcogenide waveguide platform which will subsequently be implemented on an on-chip spectrometer that will operate in the long-wave IR spectral region.

FABRICATION

The proof of principle on-chip spectrometer we are developing is using a simple and efficient thermo-optically tuneable spiral armed interferometer. The novel combination of materials used for the core and claddings in this work is GeAsSeTe (IG3) and GeAsSe (IG2), respectively. Example respective refractive index values for these layers at λ=1553 nm are 2.99 and 2.65, providing a respectable index contrast of 0.34. For the fabrication of simple straight waveguides that can be used in a variety of applications ranging from biomedical sensing to non-linear optical processing, a simple wet etching method was utilised which consisted of buffered oxide etch and KOH etch. By using [110] Si wafers and exposing them to a KOH solution after proper mask alignment, completely vertical sidewall Si pedestals were fabricated. With subsequent evaporation of the optical layers, ridge waveguides were defined as we have also reported in [8]. Since the sidewall angle is dictated by the Si plane directions in the wet etching method, this method is not suitable for devices with structures that cross multiple planes/directions such as bends, spirals and splitters and a dry etching method is required. We have exploited a dry etching to create waveguide-based components such as splitters and spirals required for our on-chip spectrometer. To minimise the sidewall deposition of waveguide materials during the evaporation, we required negative (re-entrant) sidewalls during dry etching. For the patterning of pedestals with such characteristics we studied and used a Bosch process and a pseudo-Bosch process. Example waveguides fabricated using the wet (Fig. 1 a-c) and dry (Fig. 1 d-f) etch methods are presented below.

RESULTS AND DISCUSSION

The propagation loss was estimated for the wet etched pedestal waveguides using the scattering streak fitting method. An infrared camera collected the scattered light emanating from the top surface of the waveguides (Fig. 1 g and by exploiting the decaying nature of the light streak, the propagation loss was estimated for two different waveguides (1 and 2), for TE and TM polarisations between λ = 7 and 11 µm and is shown in Fig.1 i. The overall loss is showing a decreasing trend with wavelength which agrees with reduced scattering at longer wavelengths. The peak observed at λ = 8 µm for TE polarisation was attributed to Ge-O related vibrations. Similar absorption bands have also been reported in GeAsSeTe fibres [9].

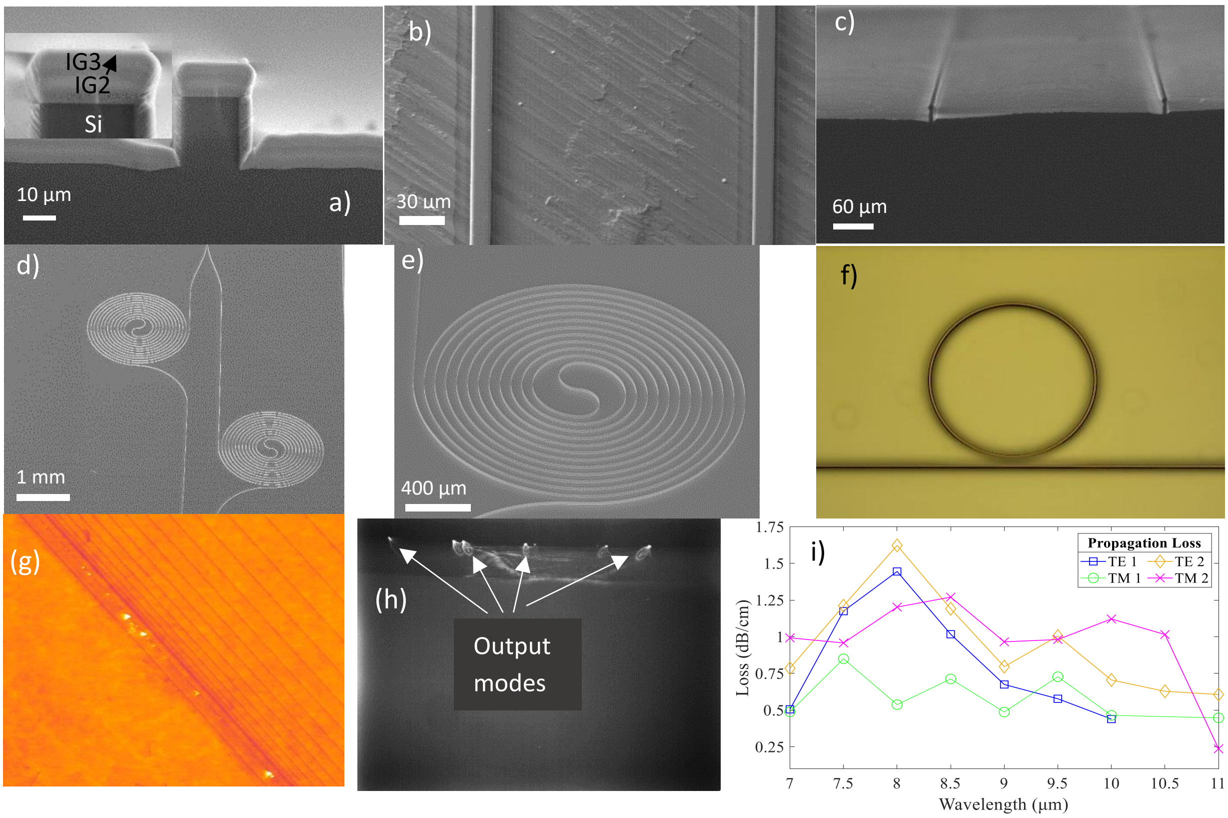

Fig. 1. a) Cross-section of 26.5 µm wide wet etched waveguide (IG3 core: ~3.6 µm, IG2 cladding ~7 µm, IG2 capping layer ~250 nm) , b/c) top /tilted view of wet etched waveguides, d) dry etched spiral Mach-Zehnder interferometer (MZI), e) close view of

dry etched spiral, f) dry etched ring resonator, g) scattering on the surface of a wet etched waveguide at λ = 9 μm, h) output modal spots of dry etched splitter, i) propagation loss estimation

As can be seen in Fig. 1 a-c, the fabricated pedestal waveguides have very smooth surfaces with no observable interfacial cracks or large grain structure. This is also reflected in the low estimated propagation losses which according to our estimations, average about 0.9 dB/cm in the long-wave IR spectral region.

The dry etched pedestal waveguide platform presented above is employed on our on-chip spectrometer design which is currently under fabrication. With the insight provided by our current characterisation results, we believe that the platform has huge potential for use in on-chip spectrometers as well as integrated sensor devices. As discussed before, our spectrometer design is based on a simple thermo-optically tuneable MZI. For such a device to be efficient, the waveguide materials should possess good thermo-optic properties. Using the thermo-optic coefficient values of the bulk chalcogenide glasses and after a quick estimation we predict that the thermo-optic performance of the spectrometer will be similar to that of a Si based one.

CONCLUSION

The low optical losses demonstrated here coupled with the ease and straightforwardness of the fabrication of this waveguide platform, could pave the way for wider use of chalcogenides in integrated mid-IR waveguide applications. We have shown propagation losses as low as 0.5 dB/cm in the long-wave IR which are among the lowest reported for integrated chalcogenide waveguides. In addition, the novel material combination of the optical layers used in this work, not only is characterised by low losses, good index contrast and wide transparency up to 12 μm, but it is also expected to perform very efficiently as a thermo-optic medium for on-chip spectrometer application due to its good thermo-optic coefficient as well as inherently low thermal conductivity.

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